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Superimposed beam deflection using acousto-optical deflectors in combination with a galvanometer scanner

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Abstract

We report on the deflection behavior of a combined scanning system consisting of two acousto-optical deflectors (AOD) and a galvanometer scanner for ultra-short laser pulses. To fundamentally characterize the scanning movement of the hybrid system, the roundness of the focal spots within an AOD scan field and its dimensions are analyzed by ablated geometries in thin indium tin oxide films for different galvanometer deflections and focus levels. The investigations show that focal spots roundness of more than 90 % in a z-range of 200 µm, i.e. 36 % of the Rayleigh length, can be realized in a galvanometer scanning field of 30 x 30 mm^2. Maximum deflection speeds of 843 m/s within an AOD scan field highlight the great potential for highly dynamic laser micromachining.

Keywords: laser beam deflection; ultra-short pulse laser; acousto-optical deflector (AOD); hybridsystem;

1. Introduction

Since about two decades, the use of ultra-short pulsed (USP) lasers with pulse durations in the pico- and femtosecond range has enabled high-precision micro material processing with minimal heat input, often denoted as the so-called cold ablation [Hohlfeld, 2000]. Whereas the processing quality fulfills highest requirements, often the non-efficient utilization of the available laser power limits the extensive use in industrial applications [Finger, 2017].

Using a constant ablation efficiency, the productivity of USP laser machining processes is determined by the applied average laser power. From a very fundamental point of view, two possible scaling options for

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enhancing the productivity of USP laser based machining processes are on hand: increasing laser pulse energy or laser pulse repetition rate, in turn both scaling the available average laser power [Finger, 2017]. For efficient usage of the available laser pulse energy, diffractive optical elements (DOE's) [Haupt, 2011; Busung, 2016] or programmable phase masks, so-called spatial light modulators (SLM's) [Kuang, 2009a; Kuang, 2009b], are commonly used for splitting the beam into several partial beams, thus enabling parallel processing [Finger, 2017]. Working at higher pulse repetition rate, pulse to pulse interactions must be considered as they strongly affect the precision, productivity and overall heat input [Ancona, 2009; Finger, 2013]. Pulse to pulse interactions can be differentiated into optical interaction with a laser-induced plasma or ablation particles and heat accumulation [Finger, 2014]. To avoid these effects, a decrease of the spatial pulse-to-pulse overlap to below 50 % is necessary by increasing the deflection speed of the laser scanning system. Under this condition, Bechtold et al. have shown that the positioning frequency, which is defined as the frequency for positioning a laser spot within a scan field, of commercially used galvanometer scanners is limited to 1-2 MHz [Bechtold, 2013]. Therefore, alternative laser beam deflection technologies such as polygon scanners, electro-optical deflectors (EOD's) and AOD's [Roemer, 2014; Toyoda, 2014; Eifel, 2015] have recently attracted considerable attention.

In vector-based scanning, optical deflectors (AOD's or EOD's) are preferred because mirror-based scanner such as piezoelectric, MEMS and galvanometer scanners are limited in their dynamics due to the inertia of moving parts [Roemer, 2014]. Optical deflectors use the principle of diffraction for beam deflection, which is caused by a refractive index change in an optically transparent medium [Kirkby, 2010]. Two perpendicular aligned AOD's are required for a 2D scan unit, since one AOD deflects the laser beam in only one direction. However, this combination just allows beam deflection in an angle of θ = 0.01 - 0.05 rad [Roemer, 2014]. Therefore, AOD subsystems are combined with galvanometer scanners for increasing the scanning area.

The applicability of such scanning systems has already been demonstrated for industrial applications [Bechtold, 2013; Eifel, 2015; Bruening, 2016]. However, the superimposed scanning movement has not yet been fundamentally characterized to clearly resolve and evaluate its potential for high-dynamic laser micromachining. In this study, we comprehensively characterize the scanning movement of such a hybrid system, combining two AOD's and a galvanometer scanner, by evaluating the laser spot roundness within an AOD scan field and its dimensions using different galvanometer deflections and focal levels by ablated geometries in thin indium tin oxide (ITO) films.

2. Experimental

2.1. Hybrid system

The experimental setup of the superimposed laser beam deflection consisting of two AOD's (Gooch & Housego, Model AODF 4150 quartz) and a galvanometer scanner is depicted in Fig. 1. For each AOD, a 4f-setup and an aperture is used to filter the 1. diffraction order. Before entering an AOD, a half-wave plate is applied to maximize the diffraction efficiency. The used AOD subsystem, the lens combinations of the 4f-setups and the telecentric f-theta lens with a focal length of f= 100 mm enable high speed laser positioning in an AOD scan field of 630 x 630 μm^2. By diagonal laser scanning within an AOD scan field, a distance of 843 µm with a positioning frequency of 1 MHz is traversed, resulting in an AOD deflection speed of maximal 843 m/s. A galvanometer scanner is combined with the AOD subsystem for enhancing the scanning area. A USP laser (Lumentum, Picoblade 2) with a wavelength of λ= 532 nm, a laser pulse duration of τ= 5 ps and a beam quality of M^2 < 1.3 was used at a laser pulse repetition rate of f= 2.2 MHz for experimental investigations.

2.2. Characterization of the superimposed laser beam deflection

In all investigations, ablation of ITO thin films with a thickness of 110 nm serves for characterization of the superimposed beam deflection. The analysis of ablated geometries in ITO can be used for determination of the laser beam profile at defined focal positions [Rung, 2014].

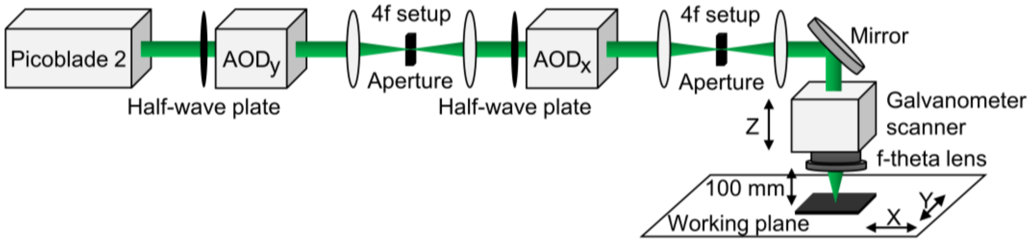


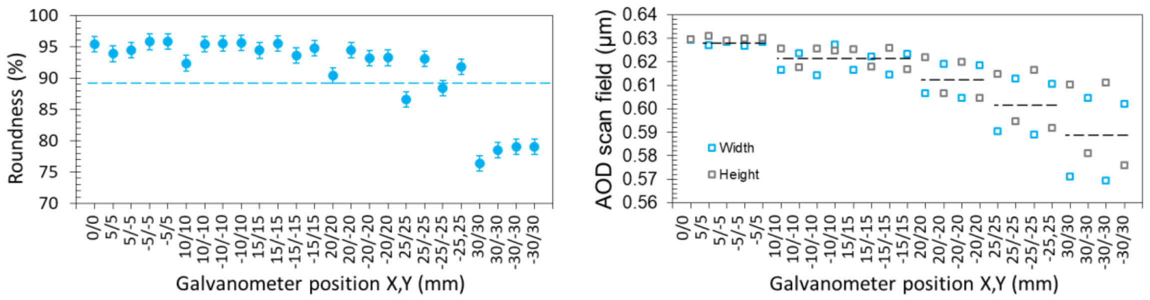
Fig. 1. Experimental setup for characterization of the superimposed laser beam defection using two AOD's and a galvanometer scanner.

A fundamental precondition for the applicability of the hybrid system is a constant laser beam profile and a high accuracy in beam positioning within the focal plane of the f-theta lens and Rayleigh length. In order to detect a modification of the Gaussian laser pulses, AOD grids with 13 x 13 regularly arranged spots were ablated in ITO material at different galvanometer deflections of ± 30 mm and z-levels of +/- 500 µm. For evaluation of the spots roundness, processing results were recorded with a resolution of 0.24 µm/pixel by using a microscope (Leica DM6000 M). The ratio of minimal and maximal diameter of ablations, which were determined from the microscope images using an ad-hoc made Matlab routine, defines the spot roundness.

3. Results and Discussion

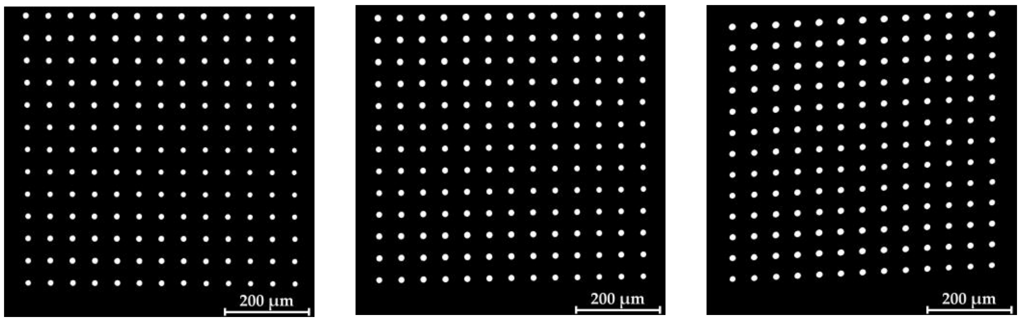
3.1. Characterization within the focal plane of the f-theta lens

The averaged roundness of the ablation grids in ITO material within an AOD scan field and its standard deviations in the focal plane of the f-theta lens depending on different galvanometer deflections is depicted in Fig. 2(a). For the evaluation of spot roundness, the typical specification for micro holes with a circularity of > 90 %, e.g. microvias in printed circuit board material (Kim, 2016), are used for comparison. Spot roundness is achieved in a galvanometer deflection range of ± 15 mm with an average roundness of 94.8 % and a standard deviation of 1.6 %. The average value decreases by 3.4 % to 91.4 % applying a galvanometer deflection of ± 20 - 25 mm. The roundness of the ITO ablations is consistently lower at upper right galvanometer deflections in comparison to the others, cf. Fig. 2(a). As a result, the roundness specification cannot be completely fulfilled using galvanometer deflections of ± 20 mm. This effect is caused by a non-centric and parallel propagation of the laser radiation through the telecentric f-theta lens. However, roundness specifications at other galvanometer deflections in the range of ± 20 mm can be sufficiently fulfilled by an average of 93.6%.



(a) (b)

Fig. 2. Roundness of ablations in ITO material within an AOD scan field and its dimensions within the focal plane of the f-theta lens depending on the galvanometer deflection (a) Spot roundness within AOD grids; (b) Width and Height of AOD scan fields.



(a) (b) (c)

Fig. 3. Processing results of ablated AOD grids in ITO material using different galvanometer deflections in the focal plane of the f-theta lens a) 0 / 0 mm; (b) +15 / -15 mm; (c) +25 / -25 mm.

Applying galvanometer deflections from ± 25 - 30 mm, an increasing distortion of the AOD scan fields can be observed with a spot roundness of less than 90 %, which is exemplary illustrated in Fig. 3 for ITO ablations at three representative galvanometer deflections.

In addition, the dimensions of the AOD scan fields were determined depending on the galvanometer deflection within the focal plane of the f-theta lens, which are shown in Fig. 2(b). Here, the width and height of the AOD scan fields are defined as the maximal spot distances of vertical and horizontal ITO ablations. For galvanometer deflections of ± 5 mm, an averaged AOD scan field of 629 µm is achieved. The width and height of the AOD scan field decreases to 622 µm with a standard deviation of 4.6 µm by using a galvanometer deflection of ± 10 - 15 mm. At galvanometer deflections in a range of ± 20 and 25 mm, averaged AOD scan field dimensions of 608 µm are obtained with significantly larger standard deviations of 9.4 µm. The sharply decreasing AOD scan field dimensions are the result of the increasing torsion from galvanometer deflections of ± 20 mm, which is noticeable in Fig. 3(c) for the ablation result of the AOD grid in ITO material at a galvanometer deflection of +25 / -25 mm. The torsion is the result of a not perpendicular laser beam in relation to the galvanometer mirrors due to different AOD deflections, causing position deviations in laser beam focusing. In general, the f-theta lens is calibrated to the used lens and scanner by a slightly modification of the scanning angle [Gillner, 2019]. Using the superimposed beam deflection, the position deviations at different galvanometer deflections must be compensated by adapting the applied AOD sound frequencies.

Overall, a spot roundness within an AOD scan field of > 90 % by using galvanometer deflections of ± 15 mm is demonstrated. Consequently, the usable scanning area of the hybrid system is more than halved as compared to galvanometer scanners. In order to achieve a high accuracy in laser beam positioning, a calibration of the scan field dimensions as a function of the galvanometer deflection is indispensable.

3.2. Characterization within the Rayleigh length

The roundness of ITO ablations within an AOD scan field and their dimensions were analyzed depending on the galvanometer deflection in a range of ± 25 mm and the z-level of ± 500 µm. For illustration, the results of a non-deflection, a galvanometer deflection of +15 / -15 mm and +25 / -25 mm are depicted in Fig. 4, where the AOD scan field dimension is defined as the average of its widths and heights. An average roundness of 94.2 % with a standard deviation of 1.2 % is achieved by a non-deflection of the galvanometer scanner in a z-level area of –100 µm to +200 µm regarded to the f-theta focal plane, cf. Fig. 4(a). The AOD scan field dimensions increase continuously from 629 to 632 µm within this z-level area. The maximum roundness value with an average of 96.7 % is reached in a z-level 50 µm below the focal plane.

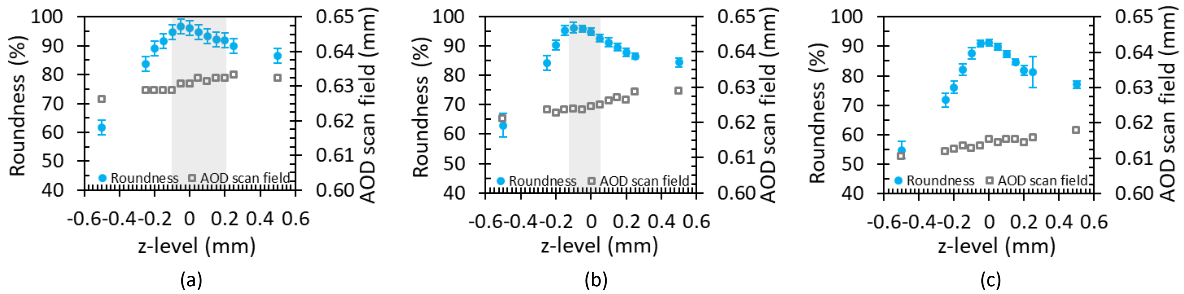


Fig. 4. AOD scan field size and spot roundness of ablation in ITO material in dependence of galvanometer deflection (a) 0 / 0 mm; (b) + 15 /- 15 mm; (c) + 25 /- 25 mm.

Compared to the non-deflection of the galvanometer scanner, Fig. 4(b, c) shows exemplary the averaged roundness and the AOD scan field dimensions at galvanometer deflections of ± 15 – 25 mm depending on different z-levels. The focal level area with spot roundness of more than 90 % is reduced by 100 µm to +50 to -150 µm in relation to the focal plane using a galvanometer deflection of ± 15 mm. An averaged spot roundness of 94.7 % and standard deviations of 1.3 % within an AOD scan field are achieved. The dimension of the AOD scan fields decreases by 7 µm to an average of 624 µm compared to the non-deflection of the galvanometer scanner. Industrial roundness specification of > 90 % cannot be fulfilled by using a galvanometer deflection of ± 25 mm, which is in agreement with the findings from the previous roundness analysis within the f-theta focal plane. The averaged AOD scan field size is reduced to 614 µm.

In summary, roundness of ITO ablations > 90 % within an AOD scan field are demonstrated within an z-level area of 200 µm using a galvanometer deflection of ± 15 mm. In order to achieve a high accuracy in laser beam positioning, different AOD scan field dimensions of up to 7 µm must be considered in dependence of the galvanometer deflection. Furthermore, processing within the focal plane of the f-theta lens is mandatory because modified AOD scan field dimensions of up to 3.5 µm could be identified within the Rayleigh length by using different galvanometer deflections.

4. Conclusion

In this study, a superimposed laser beam deflection system consisting of two acousto-optic deflectors and a galvanometer was fundamentally characterized. Here, the roundness of ablations in ITO thin films within an AOD scan field and its dimensions were analyzed as a function of different galvanometer deflections and focal levels. The applicability of the hybrid system is demonstrated within a galvanometer scanning area of 30 x 30 mm^2 and a z-level area of 200 µm. In order to achieve a high accuracy in beam positioning for applications in laser micromachining, different AOD scan field dimensions of up to 6.9 µm have to be considered depending on the galvanometer deflection. High deflection speeds of 843 m/s within an AOD scan field highlights the great potential of the hybrid scanning system for highly dynamic micromachining processes.

References

Ancona, A., Doering, S., Jauregui, C., Roeser, F., Limpert, J., Nolte, S., Tuennermann, A., 2009. Femtosecond and picosecond laser drilling
Assembly V, International Society for Optics and Photonics, p. 79210V.
Bechtold, P., Hohenstein, R., Schmidt, M., 2013. Beam shaping and high-speed, cylinder-lens-free beam guiding using acousto-optical
Bruening, S., Du, K., Gillner, A., 2016. Ultra-fast micro machining of cylindrical parts with multiple ultra-short pulsed laser sources, Physics Procedia 83, p. 167-181.
Buesung, L., 2016. Ph.D. dissertation, RWTH Aachen University, Aachen.
deflectors without additional compensation optics, Optics Express 21, p. 14627-14635.
Eifel, S., 2015. Ph.D. dissertation, RWTH Aachen University, Aachen.
excitation of metals, Chemical Physics 251, p. 237-258.
femtosecond laser surface micro-structuring, Applied Surface Science, 255, p. 6582-6588.
Finger, J. T., 2017. Ph.D. dissertation, RWTH Aachen University, Aachen.
Finger, J., Reininghaus, M., 2014. Effect of pulse to pulse interactions on ultra-short pulse laser drilling of steel with repetition rates up
Finger, J., Weinand, M., Wortmann, D., 2013. "Investigations on processing of carbon fiber reinforced plastics using ultrashort pulsed
generation flexible PCB drilling, Journal of Manufacturing Systems 38, p. 107-113.
Gillner, A., Finger, J., Gretzki, P., Niessen, M., Bartels, T., Reininghaus, M., 2019. High power laser processing with ultrafast and multi-
Haupt, O., Schuetz, V., Stute, U., 2011. "Multi-spot laser processing of crystalline solar cells", Laser-based Micro-and Nanopackaging and
Hohlfeld, J., Wellershoff, S. S., Guedde, J., Conrad, U., Jaehnke, V., Matthias, E., 2000. Electron and lattice dynamics following optical
Kim, K. R., Cho, J. H., Lee, N. Y., Kim, H. J., Cho, S. H., Park, H. J., Choi, B., 2016. High-precision and ultrafast UV laser system for next-
Kirkby, P. A., Nadella, K. N. S., Silver, R. A., 2010. A compact acousto-optic lens for 2D and 3D femtosecond based 2-photon microscopy,
Kuang, Z., Liu, D., Perrie, W., Edwardson, S., Sharp, M., Fearon, E., Dearden, G., Watkins, K. , 2009. Fast parallel diffractive multi-beam
Kuang, Z., Perrie, W., Liu, D., Edwardson, S., Cheng, J., Dearden, G., Watkins, K., 2009. Diffractive multi-beam surface micro-processing
laser radiation with high average power", International Congress on Applications of Lasers & Electro-Optics, Institute of America, p. 560-560.
Micromachines 5, p. 943-953.
of metals at high repetition rates and average powers, Optics Letters 34, p. 3304-3306.
Optics Express 18, p. 13720-13744.
parallel beams, Journal of Laser Micro/Nanoengineering 14, p. 129-137.
Roemer, G. R. B. E., Bechtold, P., 2014. Electro-optic and acousto-optic laser beam scanners, Physics Procedia 56, p. 29-39.
Rung, S., Barth, J., Hellmann, R., 2014. Characterization of laser beam shaping optics based on their ablation geometry of thin films,
The Journal of Engineering 2014, p. 81-82.
to 10 MHz, Optics Express 22, p. 18790-1879.
Toyoda, S., Sasaki, Y., Kobayashi, J., 2014. Improvement of 200 kHz optical beam scanner performance with multiple internal reflection,
using 10 ps laser pulses, Applied Surface Science 255, p. 9040-9044.